Naval Research Laboratory

Washington, DC 20375-5320

NRL/MR/6180--97-8107

An Investigation of Air Emission Reduction Methods for Aircraft Rescue and Firefighter Training Fires: Small-Scale Tests

M.J. PEATROSS
R.J. OUELLETTE
D.P. VERDONIK

Hughes Associates, Inc., Baltimore, MD

F.W. WILLIAMS

Navy Technology Center for Safety and Survivability
Chemistry Division

November 20, 1997

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave Blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	November 20, 1997	Final Report 1996-1997

4. TITLE AND SUBTITLE

An Investigation of Air Emission Reduction Methods for Aircraft Rescue and Firefighter Training Fires: Small-Scale Tests

5. FUNDING NUMBERS

6. AUTHOR(S)

M.J. Peatross*, R.J. Ouellette*, D.P. Verdonik*, and F.W. Williams

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Naval Research Laboratory
Washington, DC 20375-5320

8. PERFORMING ORGANIZATION REPORT NUMBER

NRL/MR/6180--97-8107

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Naval Air Systems Command
Department of the Navy
Washington, DC 20361-1205

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

*Hughes Associates, Inc., Baltimore, MD

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Small-scale experiments were conducted to examine pollutant reduction techniques for JP-5 spray fires. These tests were part of a program to relocate the fire training facility at Naval Air Training Center (NATTC) Millington to NATTC Pensacola. The use of water spray, fuel additives, and water emulsion was investigated. Water spray was identified as the most feasible technique for immediate use at the facility. The water spray system was optimized by examining nozzle spray characteristics, nozzle configurations, and water-to-fuel ratios. A smoke reduction of 96 percent was achieved for a water-to-fuel ration of 9.1. Emissions factors for carbon monoxide, sulfur dioxide, nitric oxides, and total hydrocarbons were developed. These factors provide a better estimation of fire trainer emissions than those currently available.

14. SUBJECT TERMS

Spray fires	Pollutants	Emission factor
Firefighting	Smoke reduction	Water emulsion
Water spray	Fuel additives	Firefighter training

15. NUMBER OF PAGES

47

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std 239-18
298-102

CONTENTS

An Investigation of Air Emission Reduction Methods for Aircraft Rescue and Firefighter Training Fires: Small-scale Tests

1.0 INTRODUCTION

1.1 Overview

Operational requirements for Navy fire training facilities require that the fires be as close as possible to actual conditions to provide realism and to properly train the firefighters. In 1996, the fire training facility at Naval Air Technical Training Center (NATTC) Millington was relocated to NATTC Pensacola. As a result of increasing environmental concerns and the high profile location of the new training site, it was deemed important that the emission reduction techniques be improved and expanded. The facility consists of two separate trainers: the aircraft carrier deck that simulates flightdeck fire scenarios, and the fire mat that simulates flightline fires (Figure 1). The aircraft carrier deck consists of four mockups:

- Aircraft - a full size mockup of an A-7 aircraft with fire underneath wings and fuselage. Existing pollution control utilized sprayed fuel for better combustion and water overspray to reduce smoke (Figure 2).
- Engine - simulates an engine and an engine nacelle fire. Existing pollution control used sprayed fuel for better combustion (Figure 3).
- Debris Pile - creates a three dimensional fire amongst clutter. No pollution control is currently employed (Figure 4).
- Cascade - simulates a three dimensional fire for portable extinguisher training. Existing pollution control used sprayed fuel for better combustion (Figure 5).

The existing pollution control for the fire mat consisted of sprayed fuel for better combustion and water overspray to reduce smoke.

These fires drive the size beyond that which can economically be performed indoors. In turn, being outdoors greatly limits the available pollution control technologies that can be employed to reduce the emissions. Emissions from these training facilities can not be trapped or treated prior to being emitted. A further result of the fire size is that full-scale fires can not be performed in instrumented facilities to characterize and measure the emissions.

Manuscript approved October 2, 1997.

Fig. 1 — Fire mat mockup

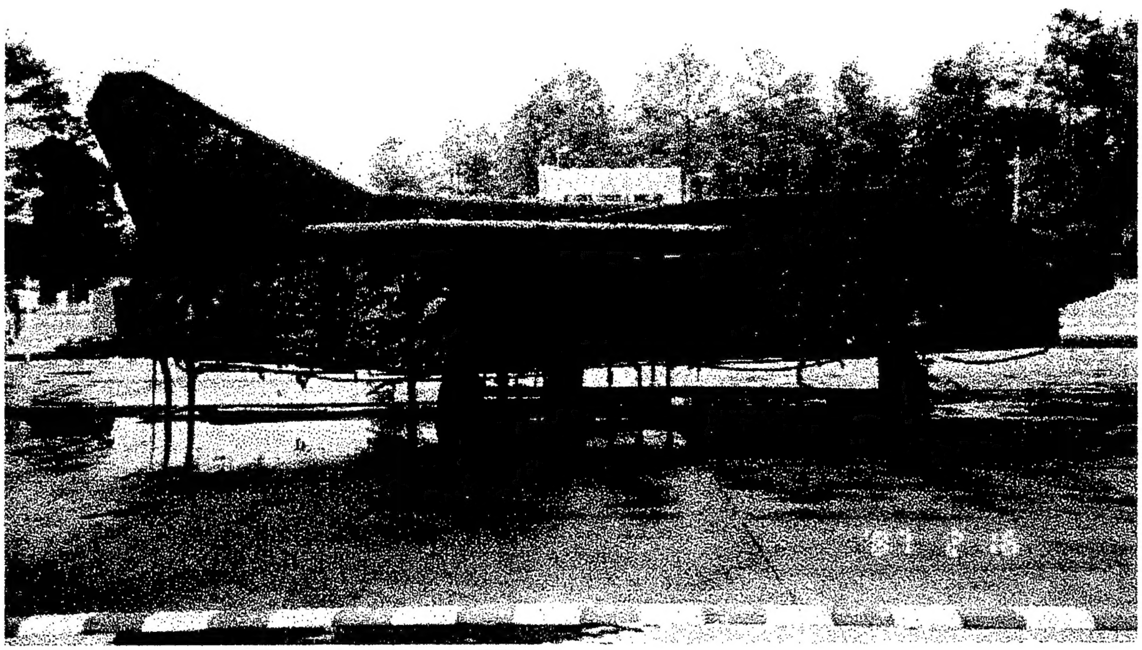

Fig. 2 — Aircraft carrier deck aircraft mockup

Fig. 3 — Aircraft carrier deck engine mockup

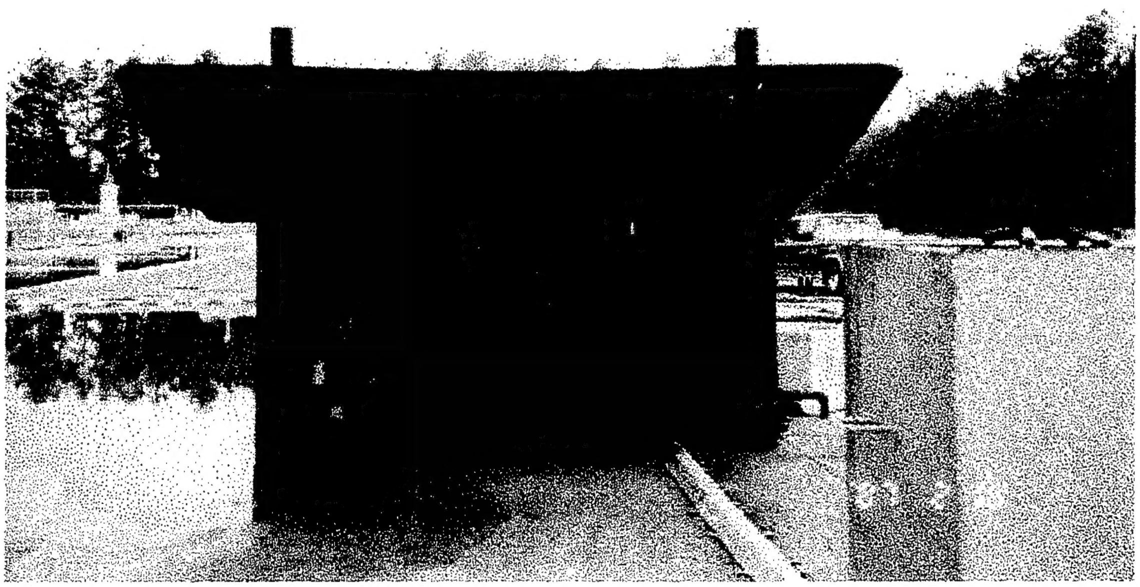

Fig. 4 — Aircraft carrier deck debris pile mockup

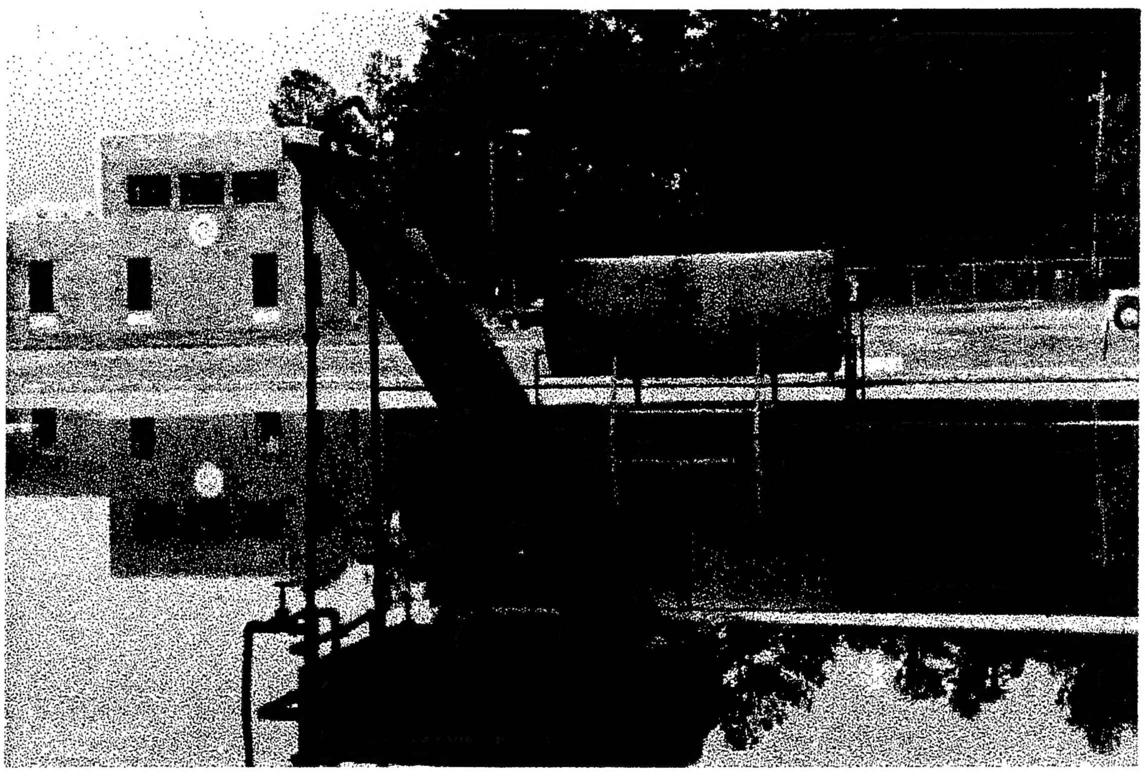

Fig. 5 — Aircraft carrier deck cascade mockup

Most significant emission sources are regulated by the Clean Air Act (CAA) as amended in 1990. The CAA establishes National Ambient Air Quality Standards (NAAQSs) that provide thresholds for air pollutants. These thresholds are determined by the U.S. Environmental Protection Agency (EPA) and represent a level at which no adverse effects to humans or the environment is expected. NAAQSs exist for Ozone (and precursors), carbon monoxide (CO), Particulate Matter Less than 10 microns (PM-10s), nitric oxides (NO_X), sulfur oxides (SO_X), and lead. Areas that are at or below the levels established in these standards are in 'attainment.' Areas that are above these levels are in 'non-attainment.' Individual states are required to develop State Implementation Plans (SIPs) for all areas that are in non-attainment for any or all of the standards. As a result, specific limitations may change from state to state and region to region.

The Naval Facilities Command (NAVFAC) prepared an Environmental Impact Statement (EIS), in compliance with the National Environmental Policy Act (NEPA), for the aircraft firefighter trainer and the adjacent fire mats to be constructed at Pensacola [1]. Of particular interest to this work was (1) the wind direction and (2) the position of the training site with respect to Pensacola Bay and the barracks. The prevailing wind averages about 8.3 miles per hour. Although somewhat erratic, it generally comes from the north in the winter and the south in the summer. The erratic nature of the wind direction makes the movement of the emissions difficult to predict. However, under calm conditions, it is likely that the smoke plume will remain visible and intact for a significant time.

An application to construct an air pollution source was prepared and sent to the Florida Department of Environmental Protection (FDEP) [2]. The application included an estimate of the operation time, the fuel use and the emission of NAAQS criteria pollutants. The response from the FDEP stated that these training facilities are exempt from air pollution (CAA Title V) permitting, based on the exemption in the Florida Administrative Code (FAC) Rule 62-0210.300(3)(v). FAC 62-256.700(5) specifically allows for open burning for the purposes of instruction and training of organized firefighters [3]. At this time, there are no emission standards or pollution control devices required for firefighter training in Florida.

The lack of regulatory environmental controls for these fire trainers does not completely eliminate the environmental concerns raised. The creation of a realistic training fire will produce a 'significant' amount of emissions including visible smoke. The site arrangement of the trainers with respect to the coast line and barracks allows for the emissions to be easily seen.

1.2 History of Training Facilities

The historic training facilities for ship and aircraft firefighting employed before the late 1980's used pool fires of different jet fuels to simulate fire conditions. The pool fires were created by floating the fuels on several inches of water contained within a concrete fire mat or a soil excavated fire-pit. Mock-ups were placed within the fire mat or fire-pit to simulate actual fire conditions. Ignition of the pool fire was accomplished by addition of a highly volatile fuel added to a portion of the pool and the use of a torch. Although a burning pool fire was a very realistic training fire, the environmental, safety and health considerations were high. This method of fire training was discontinued for the following reasons:

- Igniting the highly volatile fuel with a torch is inherently dangerous and places the trainers at undue risk,

- Floating the petroleum fuels onto a concrete slab or onto soil can easily lead to ground contamination,

- Firefighting agents used to combat the fires are another potential source of ground contamination,

- Providing a large surface area of fuel allows for significant evaporation and is a considerable source of unburned fuel emissions, and

- Pool fires are inherently 'dirty' fires because they do not burn near stoichiometric air to fuel ratios (i.e., not efficient combustion).

The Navy began closing down soil fire-pits in the late 1970's and soon thereafter began upgrading concrete fire mats to incorporate fuel/water/agent collection and separation systems. These changes resolved the potential ground contamination problem but did little to resolve the safety and air pollution issues. To resolve these, the next development in fire training facilities was to replace the pool fires with sprayed fires of JP-5.

During 1987/88, the Naval Research Laboratory (NRL) conducted demonstrations of a prototype JP-5 spray fire system for the Naval Air Systems Command (NAVAIR) and the office of the Chief of Naval Education and Training (CNET). The system consisted of low-volume spray nozzles that produced an atomized fuel spray that could be remotely ignited. The resultant fire was realistic enough to adequately simulate actual fire conditions. This development served two purposes: (1) it greatly reduced the safety issue of lighting the pool fire, and (2) it reduced the pollutant emissions because spray fires burn more completely (i.e., cleaner) than pool fires.

A prototype system was tested during 1989/90 at the Shipboard Damage Control and Aircraft Firefighting School, San Diego. The requirements were that it adequately simulate actual fire conditions and that it be compatible with the afterburner smoke abatement system (SAS) already installed. The performance was judged to be acceptable and the system was accepted by the Navy. The prototype system remained in use in San Diego, while installation of these systems was planned for other schools.

During the same time, construction was underway for the Navy's Advanced Shipboard Aircraft Firefighter Team Training Facility at Millington, TN. The purpose of this new trainer was to simulate the conditions of firefighting on a carrier deck which required that it be an open air facility. The new JP-5 spray system was to be incorporated into the design, but due to its open-air construction, additional SAS equipment was not possible. In lieu of capturing and controlling the emissions, a new method was needed which minimized or prevented the creation of undesirable emissions, particularly visible smoke.

The possibility of using water spray/misting in conjunction with the JP-5 sprayed fuel to lower the smoke and other pollutants was then investigated. The initial concept was to scrub the

visible particles, or soot, from the fire before they have a chance to escape into the atmosphere. A prototype smoke knockdown system was developed and tested at NATTC Millington. Since these tests were run outdoors, emissions could not be collected to be fully characterized. However, based on visual observations, an approximate 75% reduction in visible pollutants was obtained. The final system was installed and certified in 1991. This system of using water overspray was deemed so successful that the Navy/Marine Shore-base Fire Facility fire mats, also located at Millington, were retrofit to include this new technology.

In addition to visible pollutant reduction through water overspray, other approaches have been developed to reduce emissions of fire training facilities. Propane has been used to replace the liquid hydrocarbon fuel with much success. Propane burns much cleaner than petroleum hydrocarbons so that visible pollutants are greatly reduced. Reductions in non-visible pollutants by using propane have also been achieved. By controlling the air to fuel ratio, it is possible to create training fires that are realistic to actual conditions and reduce the overall emissions. Premixed propane air burners with air to fuel ratios of 1.25 to 1 (gram air to gram fuel) have been shown to reduce the CO and unburned hydrocarbons by 40% of their non-premixed levels [4]. The results also indicated that there was a direct correlation between smoke reduction and CO reduction. The use of air mixed propane combustion resulted in a significant reduction in CO, particulates, and unburned hydrocarbons versus the sprayed JP-5 combustion in firefighting training facilities [4]. Another important finding of this propane work was that the CO emission reduction was independent of the burner size for the small- and intermediate-scale burners tested. This suggested that small-scale tests could be devised and run in a fully instrumented chamber and the results potentially used to develop predictions of large-scale emissions.

The large open-air training facility at Millington, TN incorporated the best emission reduction technologies available at that time. The smoke knock-down or abatement system was shown to reduce visible pollutants but further characterization of the emissions was not possible. To begin to understand the effects of the water overspray on non-visible pollutants, small-scale JP-5 pool fires, spray fires, and spray fires with water overspray were run in the burn building at NRL's fire test facility at Chesapeake Beach Detachment (NRL-CBD) in 1995 [5]. This work represented the first attempt to scientifically characterize the emissions while using the water abatement system. The results confirmed pre-test expectations. The highest level of emissions came from the pool fires while the lowest emissions resulted from the water overspray systems. All pollutants were reduced with the water overspray system. The most significant of these were visible smoke, PM-10s and benzene. These findings further confirmed that visible smoke reduction may be a good screening method to determine the extent of overall emissions reduction.

Of secondary concern to NAVFAC was the creation of the NAAQS criteria pollutants CO, SO_X, NO_X, and PM-10s. SO_X, which depends mainly on the fuel composition, may be the most important of the group because there are other significant sources of SO_X in the area [1]. These emissions were estimated by the Navy using Emission Factors from the EPA Compilation of Emission Factors [6] commonly referred to as AP-42. These Emission Factors are a standard tool used to estimate emissions when actual emission data are not available. It appears that the Emission Factors used are for burning distillate fuel in an industrial boiler. It is expected that the combustion and hence emissions for the firefighter training fires would be considerably different than for an industrial boiler. An analysis of the latest edition of the EPA Compilation of Emission

Factors does not reveal any better Emission Factors [7]. In 1995, NRL along with Hughes Associates, Inc. (HAI), characterized the emissions from JP-5 pool fires, and spray fires with and without smoke abatement [5]. Although from a limited set of fires, this data should provide a better estimate of the emissions. Table 1 shows the emissions for PM-10s and CO using the Emission Factors [7] versus the Reference 5 data in tons per year (TPY). The Reference 5 data are denoted by italics. As can be seen, the expected emissions are 1 to 2 orders of magnitude higher using the NRL data [5].

Table 1 - PM-10 and CO Emission Estimates from Emission Factors [5,7]

Fire Type/Scenario	Burn Time	Fuel Use	Fuel Use	PM-10s	*PM-10s*	CO	*CO*
	hrs/yr	gal/hr	gal/yr	TPY	*TPY*	TPY	*TPY*
Mass Conflagration	21.2	731	15,497	0.01	*0.20*	0.04	*0.86*
Debris	20.4	683	13,933	0.01	*0.38*	0.03	*1.51*
Aircraft	29.5	909	26,816	0.02	*0.10*	0.07	*0.54*
Engine	16.3	27	440	0.00	*0.00*	0.00	*0.01*
Cascade	22.4	35	784	0.00	*0.05*	0.00	*0.07*
Sub - Total:	109.8	523	57,470	0.05	*0.73*	0.14	*2.99*
Fire Mats:	325.0	876	284,700	0.26	*7.76*	0.71	*30.89*
TOTAL:	434.8	787	342,170	0.31	*8.50*	0.86	*33.88*
Emission Factor:							
lbs per 1000 gal fuel							
EPA AP-42 Data				1.80		5.00	
NRL Data					*7 - 120*		*40 - 215*

The firefighting training system at NATTC Millington used spray fires for three of the four mockups and water overspray on the aircraft mockup. However, the Navy desired to further reduce the emissions, particularly the visible smoke, from the fire trainer prior to moving it to Pensacola. Other than water overspray, the current emission reduction technique employed by the Navy was the use of cleaner burning fuels such as propane. Propane was not an acceptable alternative for use in this trainer for several reasons. The trainer has four distinct fires to simulate different firefighting scenarios. The cascading or 3-dimensional fire used for the debris pile is problematic with a fuel that gasifies as easily as propane. The other 3 fire scenarios could use propane but that would require designing and installing a new fuel system that would handle two

different fuels. There is one training scenario, referred to as Mass Conflagration, where both the aircraft and debris pile files are fought simultaneously. This would require training with two different fuels at the same time. In addition, specific safety issues arise because the propane fuel cut-off would need to be located directly at the burner to maintain positive control over the fuel. For these reasons, propane was not considered an economically-viable or safe option.

Based on this background, there was a need to continue the efforts to develop new methods to achieve reductions in emissions of large open-air fire trainers. Visible smoke reduction is believed to be an economical screening method to assess the effectiveness of overall emissions reduction. This provides a means to look at a wide range of options, e.g., clean liquid fuels, additives to the fuels, refined water overspray methods, etc. Since the smoke is largely responsible for creating the visible orange flame that is characteristic of a 'real' fire, there is a limit to the amount of smoke reduction that can be incorporated before the training fire becomes inadequate (unrealistic). Further, because smoke, CO, and unburned hydrocarbons appear to be affected in the same manner, smoke reduction may be the limiting factor in reducing the overall emissions.

2.0 OBJECTIVES

The overall objective of these tests was to identify more effective smoke reduction techniques to be incorporated into the fire trainer for NATTC Pensacola. This included investigation of the performance of various smoke abatement techniques, improvement of the most promising techniques by systematically optimizing the design parameters, and characterization of the emissions from the final design. These results were used to prepare the final designs for the fire trainers at NATTC Pensacola.

One important consideration in identifying viable techniques was to maintain the firefighting realism, as measured by heat output of the fire and overall appearance. It was likely that improvements in the emissions would affect the firefighting realism of the fire so that some tradeoffs would be necessary in determining the final system. Another consideration was that the fires should appear as a single, homogeneous fire as much as possible rather than distinct, separate fires to better simulate actual firefighting conditions.

3.0 APPROACH

Initially, tests were conducted to identify parameters which are critical to the design. It was suspected that these parameters would include but not be limited to the following:

- Nozzle spray characteristics
- Nozzle configuration
- Water-to-fuel ratio
- Fuel additives/emulsions

Upon identification of the critical parameters, the system was then optimized to accommodate the different geometries involved in the mockups. Following these optimization tests and prior to the final test series, full-scale tests were conducted to evaluate these designs. Results from these tests are reported separately [8]. Using the designs that resulted from full-scale validation, small-scale tests were conducted to perform characterization of emissions for the final aircraft and fire mat designs.

4.0 EXPERIMENTAL SETUP

Fire tests were conducted in the NRL-CBD burn building. This facility is fully enclosed and houses a 6.1 m by 6.1 m instrumented hood which uses oxygen depletion calorimetry to measure the rate of heat release of a fire [9]. All fire effluent is drawn through the hood via an exhaust fan and can be sampled for smoke and chemical composition measurements. As a result, the fire size was limited by the ability of the fan to exhaust the building. All tests used JP-5 as the fuel. Figure 6 provides a schematic of the fueling system used for all of the tests.

Continuous gas analyzers were used to measure the emissions of carbon monoxide, (CO), carbon dioxide (CO_2), total hydrocarbons (THC), and oxygen (O_2) for all tests. Analyzers consisted of the following models and ranges:

- Rosemount model 880A CO analyzer (0-100 ppm range),
- Beckman model 865 CO_2 analyzer (0-2.5% range),
- Rosemount model 440A THC analyzer (0-1000 ppm C_2 range), and
- Servomex model 540A O_2 analyzer (17%-22% range).

Figure 7 shows the schematic of the emissions data collection system. Two gas samples lines were used, one for CO, O_2, and CO_2 and a separate line for the total hydrocarbons. The THC line was wrapped with heat tape to maintain the gas sample temperature above 50°C. The heated sample line was important to prevent hydrocarbons from condensing onto the tubing walls. The main sample passed through an ice bath, a particle filter, and a water trap prior to entering the analyzers. The THC gas sample line branched off of the stack at approximately the same spot and passed through a Gelman Filter.

Final full-scale characterization tests also incorporated analyzers to measure NO_X and SO_2 as well as an additional THC analyzer. Nitric oxides and sulfur dioxide were sampled through the same probe as CO, O_2, and CO_2. A VIA Model 2-2 dual gas conditioner was used to trap out the water in this sample line. A sample line with a built-in heating jacket was installed for the THC measurements. The analyzers and corresponding ranges used were

- Thermo Environmental Instruments Model 42H NO_x analyzer (0-100 ppm range),
- Western Research Model 721M SO_2 analyzer (0-100 ppm range), and
- Thermo Environmental Instruments Model 51 (heated) THC analyzer (0-1000 ppm C_2 range).

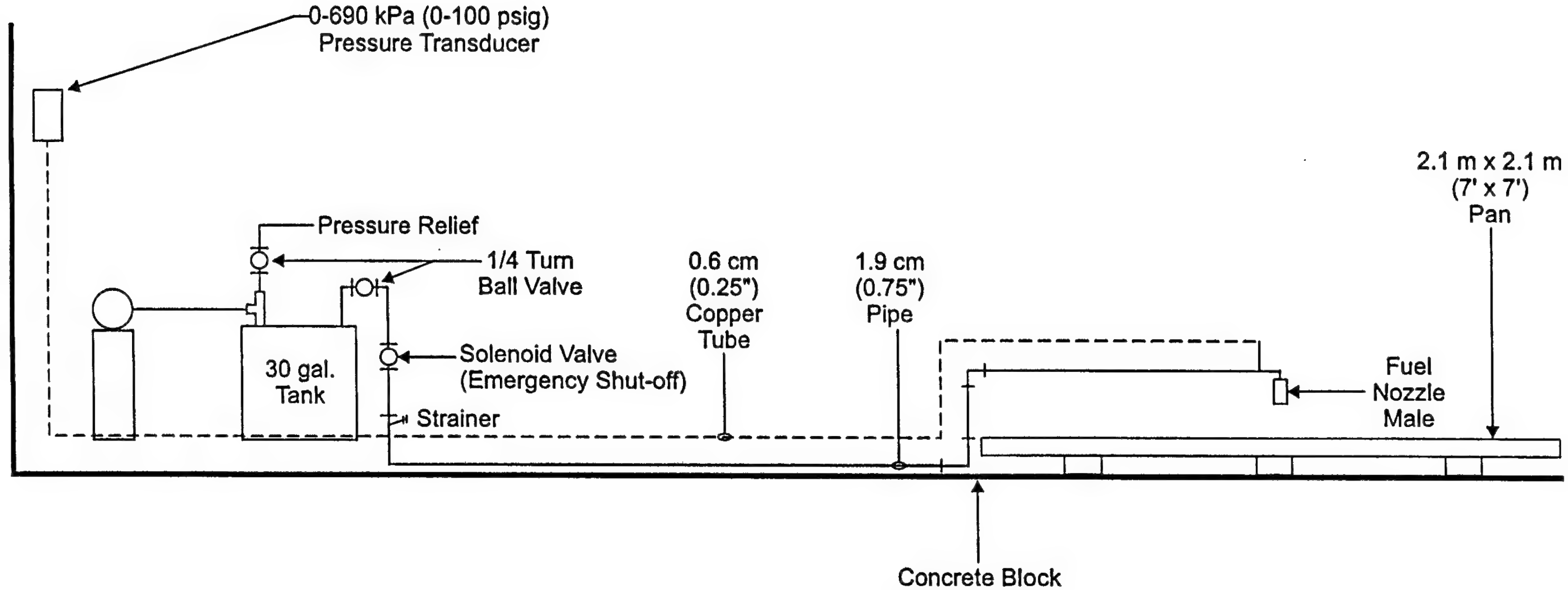

Fig. 6 – Schematic of fueling system

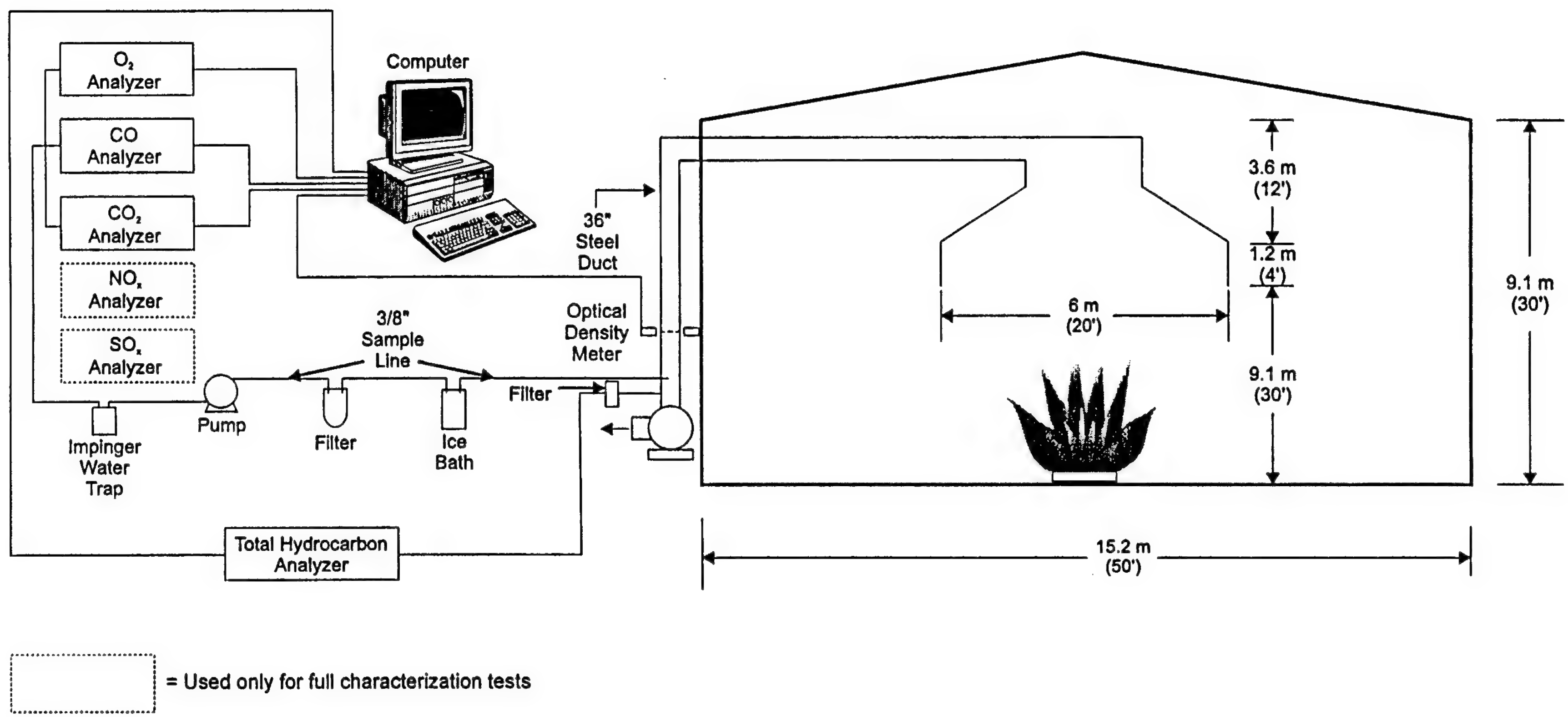

Fig. 7 – Schematic of gas analyzer system

Continuous optical density measurements were made using a 670 nm diode laser with a pin silicon photodiode positioned across the exhaust stack. Heat flux was measured by a 5 kW/m^2 radiometer (Medtherm Corporation model 64-0.5-20).

In addition to this instrumentation, other data recorded was

- Fan speed,
- Fuel pressure using a 0 - 100 psi pressure transducer (Omega PX302-150GV),
- Water pressure with a 0 - 100 psi pressure gauge,
- Air pressure,
- Stack temperature and THC line temperature using K-type thermocouples,
- Ambient temperature,
- Relative humidity, and
- Barometric pressure.

Visual recordings were made of each test. There were two stationary video cameras. One of these cameras was located in the burn building recording the fire and the other was positioned to record the smoke plume exiting the fan/stack. Photographs were also taken of the fire and the smoke plume.

5.0 PROCEDURES

5.1 Test Procedures

Each day, the test setup was checked and gas analyzers were calibrated, as indicated in the Test Setup, Analyzer and Apparatus Check Sheet provided in Appendix A. The first test of the day was a 56 cm pan fire which warmed up the hood and stack, and provided a check to ensure the analyzers were working properly. Prior to each test the Pre-test Check List and the Pre-test Data List from the K-36 Smoke Abatement - Test Data Sheet, also provided in Appendix A, were completed. The data acquisition system and the two video cameras were started simultaneously to mark the beginning of each test. Sixty seconds of baseline data were recorded before the fuel was turned on and ignited using a propane torch. For the tests with water overspray, the water was turned on a few seconds after the fuel was ignited. Once the fuel (and water if applicable) was adjusted to the proper pressure, the fire was allowed to burn for five to ten minutes allowing steady-state conditions to be established. Photographs were taken of the fire and the smoke exhaust. For the fires with water overspray, the water system was shut off after ten minutes and the fire was allowed to burn for an additional five minutes. The photographs and visual estimation of the smoke opacity were recorded without the water overspray for comparison. During the test, the participants watched for potentially clogged nozzles (indicated by smaller flame volume) or fuel vaporization in the line. If these conditions were observed, the test was terminated early.

5.2 Data Analysis Techniques

Data were averaged over a period of 150 to 300 seconds during the steady-state portion of the test. The amount of smoke produced during the test was expressed as the smoke yield. The smoke yield is defined as the mass of smoke produced normalized by the mass of fuel burned. This allowed easy comparison between tests with different fuel flow rates. Fuel and water flow rates were calculated using the supply pressure and the orifice flow coefficients supplied by Bete Fog Nozzle for water flow. Since these coefficients are specific to water, the fuel flow rates were corrected using the specific gravity of JP-5 resulting in a correction factor of 1.11.

Another important consideration was to correct for dilution of the exhaust gases. The fire effluent was diluted with ambient air as it was drawn into the hood, also diluting the gas concentrations. There is no straightforward and reliable way of measuring this amount of dilution. The approach that was used for this analysis was to assume that the fuel burned stoichiometrically to form only carbon dioxide and water. The dilution ratio was calculated by determining the ratio of the dry stoichiometric carbon dioxide concentration (assumed fuel composition of $C_{11}H_{22}$) to the measured carbon dioxide concentration. It is realized that this is an idealized assumption as indicated by the measurement of carbon monoxide and unburned hydrocarbons. Both of these species are products of incomplete (non- stoichiometric) combustion. Furthermore, this assumption does not account for the carbon dioxide that is in the dilution air (generally about 300-350 ppm). These issues reflect the uncertainty and difficulty associated with this type of experiment. As a result, a large degree of variation exists in the gas concentration results.

6.0 RESULTS AND DISCUSSION

6.1 Scoping Tests

Tests were conducted initially to identify the parameters that have the most impact on the effectiveness of the smoke abatement system. These parameters included: nozzle geometry, nozzle spacing, water-to-fuel ratio, and additives/emulsions. The results from these tests are summarized below.

6.1.1 Nozzle spray characteristics

The objective of these tests was to identify fuel and water nozzles which were the most suitable to reduce smoke and other emissions while maintaining realistic training fires. One consideration was the flow pattern which includes the angle of spray coverage and the shape of the spray (i.e., flat spray, full cone, hollow cone). Another consideration was the drop size produced by the nozzle. The drop size is a function of the nozzle shape and the pressure at which the fluid is supplied. Generally, the smaller the size of the fuel droplet, the cleaner it will burn. Because of this, two air atomized nozzles were also tested in addition to the single fluid nozzles.

Two types of single fluid nozzles, manufactured by Bete Fog Nozzle Inc., were examined for use as fuel nozzles (L and P series). A photograph of a representative fire is included in Figure 8. The L series nozzle is a low flow nozzle with a 90° hollow cone spray pattern. The P series nozzles is a low flow, fine atomization nozzle with a 90° full cone spray pattern. There was not a significant difference in smoke production between these nozzles. Furthermore, the P nozzle was found to be less durable than the L nozzle. The metal hook the P nozzle used to atomize the spray was easily bent. The fire produced with the P series nozzle was less realistic looking than for the L series nozzle with the same fuel flow rate. For these reasons, the L series nozzle was chosen for further testing.

Two air atomized nozzles were also tested. These nozzles were model numbers JSU79 and SU22B manufactured by Spraying Systems, Inc. Neither of these nozzles produced satisfactory fires. The fire that resulted with the JSU79 nozzle was sooty. Likewise, the fire that resulted with the SU22B fire was either sooty when there was little or no air pressure supplied, or was jet-like when the air pressure was increased. Both of these nozzles were abandoned.

Two types of nozzles, TF120 (manufactured by Bete Fog Nozzle, Inc.) and L, were evaluated for use as water spray nozzles. The TF120 series nozzles have a 120° full cone spray pattern. The smoke reduction achieved using both types of nozzles was assessed visually. It was determined that the TF120 nozzles provided the best smoke reduction. As a result, these nozzles were used for water spray in the remaining tests.

Fuel nozzle pressures were varied to determine if droplet size affected the amount of smoke produced. Bete Fog Nozzle, Inc. recommends that their nozzles operate at pressures above 138 kPa (20 psi) to ensure that the spray pattern is uniform. The nozzles were tested in the range of 138 kPa (20 psi) to 414 kPa (60 psi). Overall, the smoke production (yield) increased with increasing fuel pressure. It was expected that for a given nozzle, increasing the fuel pressure would provide better atomization of the fuel and reduce the smoke yield. This was not observed for the nozzles tested in this study. As a result, it was determined that the fuel nozzle pressure should be as low as possible while still retaining a realistic fire. Minimizing the nozzle pressure will minimize the fuel flow rate, thus minimizing the total fuel consumption. Reduced fuel consumption will result in an overall decrease in emissions.

6.1.2 Nozzle configuration

These tests were conducted with the same setup as that used for the nozzle geometry tests except that a steel plate obstruction was added above the nozzles (Figure 9). This obstruction simulated the wing from the aircraft mockup. The addition of this obstruction resulted in a lower smoke production rate. This may be due to the fact that the steel plate provides a hot surface for the unburned or partially burned fuel to vaporize more fully and combust. The angle of the fuel spray with respect to the obstruction was examined. Four angles were used: 0°, 45°, 90°, and 180° (the 0° orientation was the spray pointed directly at the plate height). It was determined that the angle of the spray did not have a significant effect on the amount of smoke produced. However, the most realistic fire was achieved when the spray was oriented 180° from the obstruction.

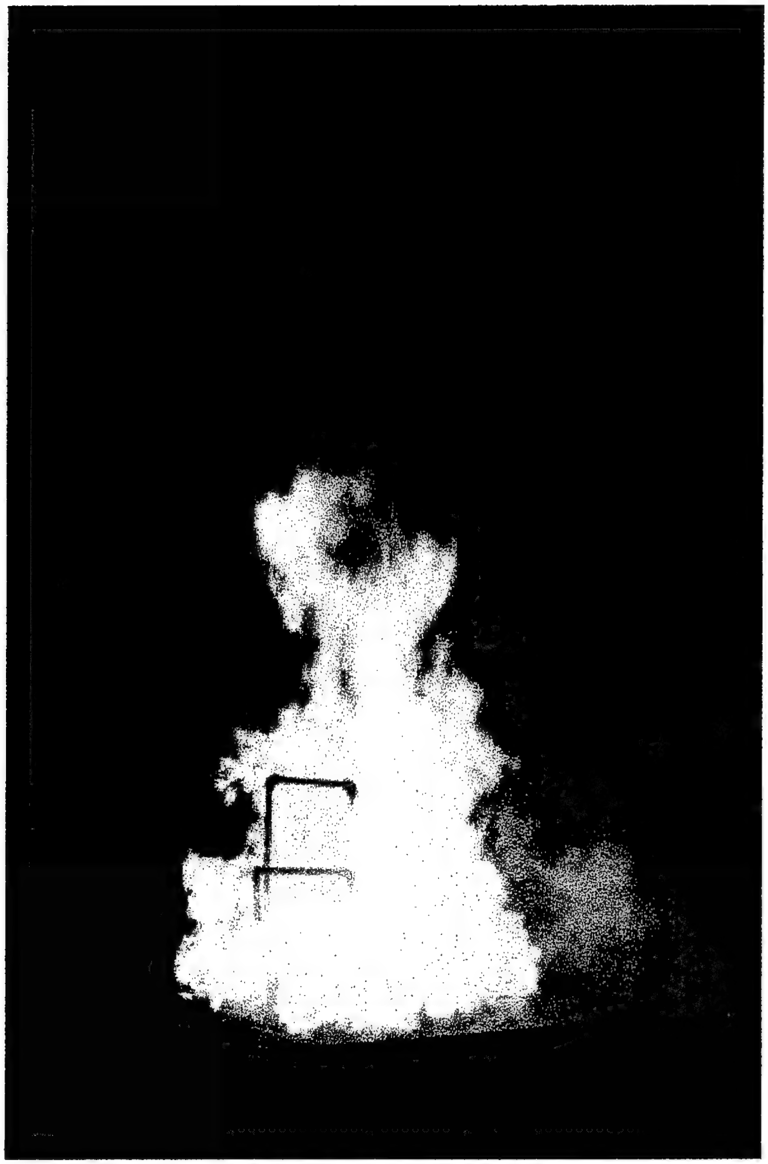

Fig. 8 — Typical fire during scoping tests

Fig. 9 — Typical fire with obstruction in place

The location of the water nozzle with respect to the fuel nozzle (180° configuration) was also investigated. The configurations examined included

- water nozzle located 15 cm directly above fuel nozzle spraying 180° from obstruction (i.e spraying in the same direction as the fuel spray, Figure 10),

- water nozzle located 30 cm directly above fuel nozzle spraying 180° from obstruction,

- water nozzle located at the same height as the fuel nozzle spaced as closely as possible spraying 180° from obstruction, (Figure 11),

- water nozzle located 15 cm below the fuel nozzle spraying 180° from obstruction, and

- water nozzle located 15 cm below the fuel nozzle spraying 0° to obstruction (i.e., spraying opposite the fuel spray).

The first three of these configurations reduced the smoke production, particularly the side-by-side configuration. The latter two configurations were not as effective and the fires were not realistic. Since it was important to minimize the distance at which the piping was suspended underneath the aircraft wing, the 30 cm water/fuel nozzle spacing was not investigated further. All remaining tests used either the 15 cm fuel/water nozzle spacing configuration (Figure 10) or the same height configuration (Figure 11).

6.1.3 Water-to-fuel ratio

The amount of smoke produced decreased as the water-to-fuel ratio (measured by volume) increased. This trend is shown in Figure 12 which shows the smoke yield as a function of the water-to-fuel ratio. These tests were conducted with an L48 fuel nozzle at a flow rate of 2.0 Lpm with a TF6FC (FC designated "full cone") water nozzle located 30 cm above the fuel nozzle. Both sprays were oriented downward. A considerable amount of scatter is noted particularly for the tests where no water was added (i.e., water-to-fuel ratio equals zero). This figure also shows the corresponding carbon monoxide concentrations. This graph suggests that the CO concentration reaches a minimum value when the water-to-fuel ratio is 1.5 and then begins to increase with increasing water-to-fuel ratio. This was a surprising result since previous testing had shown that CO and smoke follow the same trend [4].

The major tradeoff was the reduction in heat flux from the fire. This reduction was significant as noted by the test participants. Heat flux measurements were not available for these tests due to instrument problems. Quantitative measurements are discussed below in Section 6.2.1.

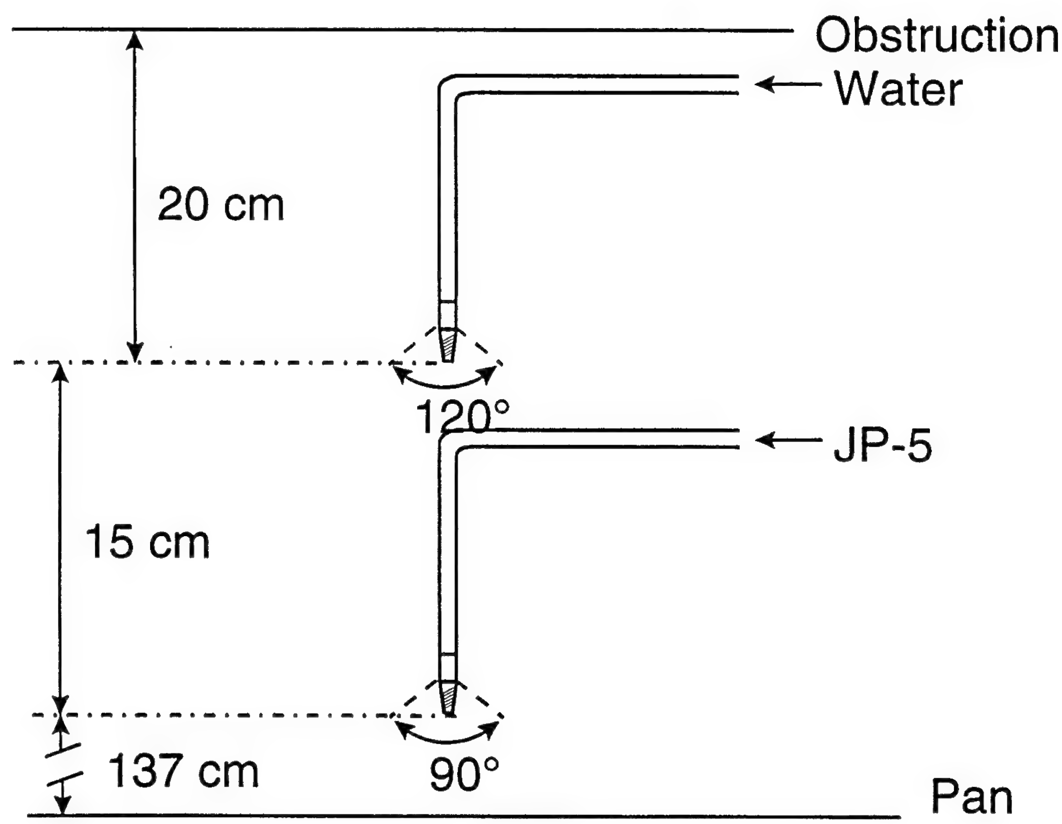

Fig. 10 – Fuel/water nozzle configuration (15 cm spacing)

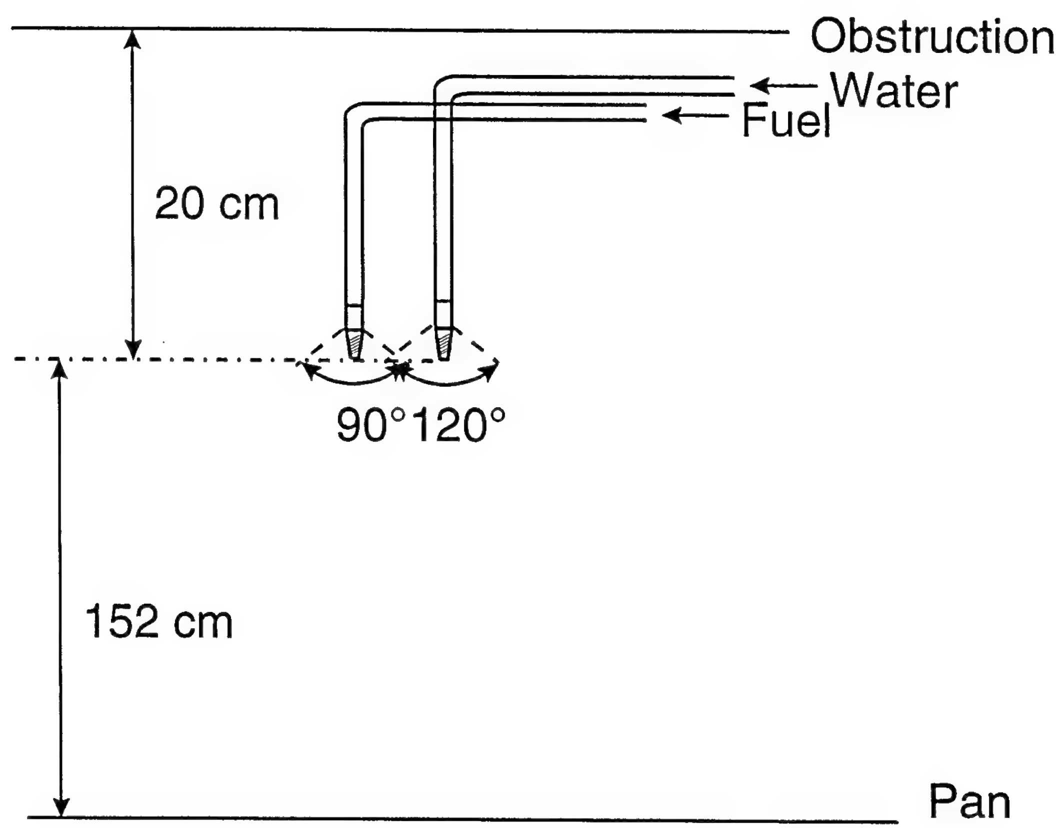

Fig. 11 – Fuel/water nozzle configuration (same height)

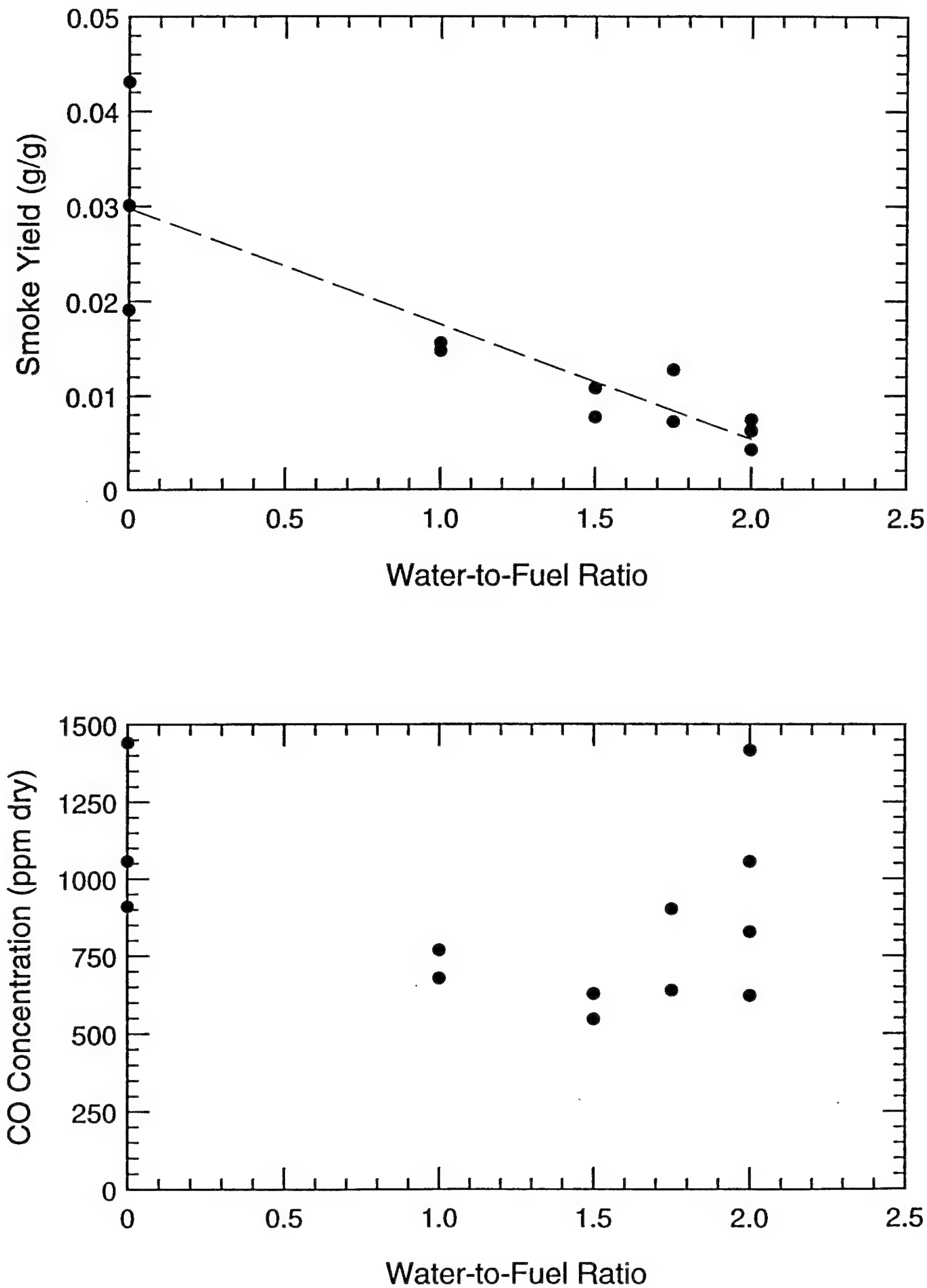

Fig. 12 – Smoke yields and CO concentrations measured as a function of water-to-fuel ratio (L48 fuel nozzle at 2.0 Lpm with TF6FC water nozzle)

6.1.4 Fuel Additives/Emulsions

Three fuel additives were tested: ethanol, methyl *tert*-butyl ether (MTBE), and ferrocene. Ethanol and MTBE were tested since they are commonly used to reduce pollutant emissions in automobiles. Ferrocene was chosen because it has also been identified as a soot inhibitor [10,11].

For tests with ethanol and MTBE, two different mixtures of JP-5 and additive were tested. These concentrations were 5% and 15% additive by mass. In all tests, the smoke production was not reduced considerably. Furthermore, flashpoint tests showed that the mixture flashpoint for both additives was close to or below ambient (25 °C). Regardless of the effectiveness of the additive, it would be unsafe to use low flashpoint fuels for training. Therefore, both MTBE and ethanol are not suitable additives.

Results with ferrocene were much more promising. Two concentrations of ferrocene in JP-5 were tested; 0.17% and 0.35% by mass. A table summarizing these results is shown in Table 2. These results show that the 0.17% mixture is nearly as effective as the 0.35% mixture. Smoke reductions ranged from 83% to 94%. With the exception of the tests conducted with the L80 nozzle, CO concentrations decreased and heat fluxes decreased slightly when ferrocene was added. Full-scale testing showed that the smoke may be reduced further with the addition of water spray [8]. However, due to the time constraints involved, the use of this additive for NATTC Pensacola could not be pursued. In order to implement its use, an environmental analysis and an occupational health study would need to be completed. Furthermore, there were potential logistical problems involving the addition of the additive to the fuel supply.

Table 2. Summary of Smoke Yields Measured with Ferrocene Fuel Additive

Fuel Nozzle (manufactured by Bete Fog Nozzle)	Concentration (%) of ferrocene by mass	Smoke Yield (g/g)	CO conc. (ppm)	Heat Flux (kW/m^2)
L80 @ 2.28 Lpm (pointing down)	baseline	0.016	2240	1.55
	0.35%	0.0010	2842	1.02
TC6FC @ 3.8 Lpm (pointing up)	baseline	0.0040	3376	1.60
	0.17%	0.0006	2975	1.83
	0.35%	0.0005	2662	1.66
FF073 @ 3.8 Lpm	baseline	0.0094	2459	1.44
	0.17%	0.0016	2401	1.28
	0.35%	0.0015	2103	1.34

Water and fuel emulsion tests were conducted where the water and fuel were turbulently mixed and discharged through a single nozzle. These tests were conducted with L80 and TF6FC nozzles. Two mixture ratios by volume were examined: 1:1 water-to-fuel (2.3 Lpm fuel and 2.3 Lpm water), and 1:3.1 water-to-fuel (2.8 Lpm fuel and 0.9 Lpm water). Table 3 summarizes the test results for the L80 fuel nozzle. The smoke reduction was dramatic for the 1:1 water-to-fuel mixture (2.3 Lpm water with 2.3 Lpm fuel), however, the flame was unstable and extinguished unpredictably. This would be unsatisfactory for a training situation. As the water concentration was reduced to try to make it more stable, the smoke level increased. It is suspected that higher levels of unburned hydrocarbons were also present as evidenced by discomfort to the participant's eyes during these tests. Only a limited number of tests were conducted to investigate this technique since there would have been logistical problems with implementing this design at NATTC Pensacola. However, this concept may warrant some future research.

Table 3. Summary of Water Emulsion Test Results with L80 Nozzle

Water flow rate (Lpm) / Fuel flow rate (Lpm)	Smoke yield (g/g)
0 / 2.3 (baseline)	0.017
2.3 / 2.3	0.004
0 / 2.8 (baseline)	0.015
2.8 / 0.9	0.014

6.2 Mockup Tests

A set of tests was performed for optimizing the smoke abatement designs for the aircraft and the engine mockups. Due to the similarities of these geometries to the cascade mockup geometry, no formal tests were conducted for the cascade. It was determined that smoke abatement would not be employed on the debris pile mockup. Therefore, no tests were devoted to this configuration. Due to limitations of the NRL-CBD burn building, the fire mat design was optimized during full-scale tests conducted at Aberdeen Proving Ground [8]. Tests using the fire mat design were conducted as part of the full characterization tests described below in Section 6.3.

6.2.1 Aircraft mockup tests

Initial aircraft mockup tests conducted in this test program were directed toward varying fuel nozzle pressures and examining water-to-fuel ratios in the range to 1.5 to 2. This range was found to provide good smoke abatement in the controlled environment of the NRL-CBD burn building. However, prior to the final small-scale test series at NRL-CBD (i.e., full characterization tests), full-scale aircraft mockup experiments were conducted. During the full-scale tests, it was determined that the wind had a serious detrimental effect on the smoke abatement system. The water-to-fuel ratio needed to be much higher than 2 to compensate for

these wind effects. Consequently, the full characterization test series incorporated much larger water-to-fuel ratios (i.e., 9.1) than had been previously tested at small-scale. Tests were conducted using the configurations shown in Figure 10 and Figure 11.

A series of tests were run with two fuel nozzles to assess the ability to use the data to predict emissions for multiple nozzle configurations. The average smoke yields for the one (fuel) nozzle and two (fuel) nozzle configurations are provided in Figure 13 for the fuel flow rate of 1.7 Lpm per nozzle and water flow rate of 15.1 Lpm per nozzle. Three configurations are shown: no water, water-to-fuel ratio of 9.1 with water 15 cm above the fuel, and water-to-fuel ratio of 9.1 with water at the same height as the fuel. The greatest smoke reduction is achieved for the case of water at the same height as the fuel. A reduction of 92% and 96% for one and two nozzles, respectively, was measured. The emissions that were typically observed exiting the exhaust stack without and with the addition of water spray are shown in Figure 14.

Average carbon monoxide concentrations measured in these same tests are shown graphically in Figure 15. The concentrations measured for the same configurations using one and two nozzles are nearly identical. The concentration increased slightly when water was added at 15 cm above the nozzle. This increase was consistent with the trend suggested in Section 6.1.3 for this same geometry. In contrast, the concentration was reduced by approximately 34% when the water and fuel nozzles were at the same height.

The reduction in heat flux (Figure 16) is nearly the same for both water locations. A reduction of 58% was measured for the 15 cm fuel/water nozzle spacing and a reduction of 56% was measured when the nozzles were next to each other. This heat flux reduction was slightly greater when two nozzles were used. A reduction of 52% was measured for the 15 cm fuel/water nozzle spacing and a reduction of 49% was measured when the nozzles were next to each other.

The results in Figures 13, 15, and 16 were also used to examine the scaling between one and two nozzle configurations. This comparison provides insights to whether single nozzle tests can be used to predict the results with multiple nozzles. The smoke yields measured for one and two nozzle tests are comparable. Based on these limited results, it appears that smoke production can be predicted to a good first approximation using the single nozzle data. However, the CO concentrations measured were nearly identical for one and two nozzle tests. This result is unexpected since the concentrations were not normalized by the fuel flow rate. The two fuel nozzle tests were expected to emit twice as much CO because twice as much fuel was burned. The heat flux data show that the fire intensity increased by approximately 50% when the fuel flow rate was doubled. These results suggest that heat flux and CO concentration can not be predicted for multiple nozzles from single nozzle data.

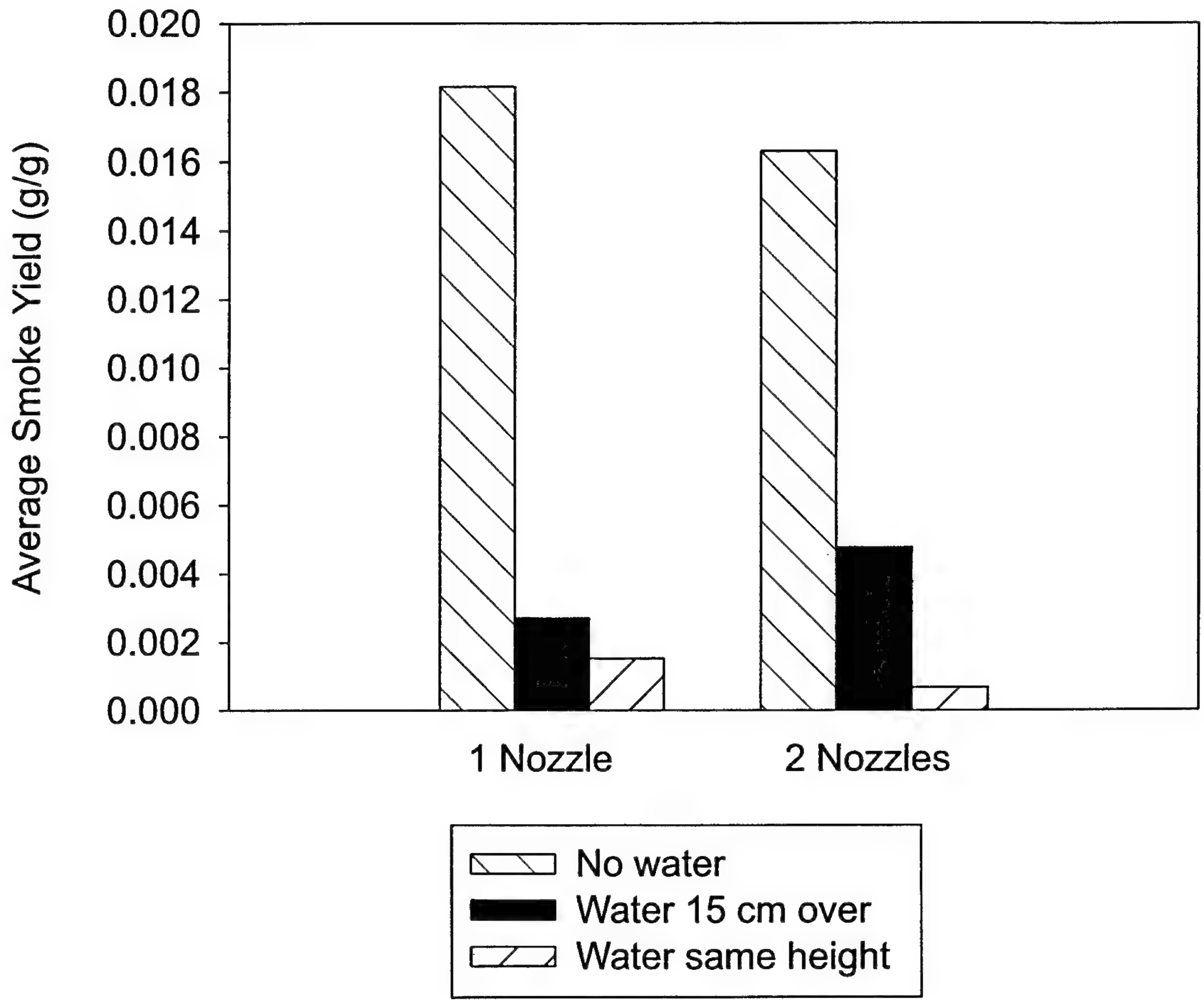

Fig. 13 – Comparison of smoke yields measured for aircraft mockup tests with and without water spray (water-to-fuel ratio = 9.1)

without water spray

with water spray

Fig. 14 — Typical fan exhaust from NRL-CBD burn facility with and without water spray

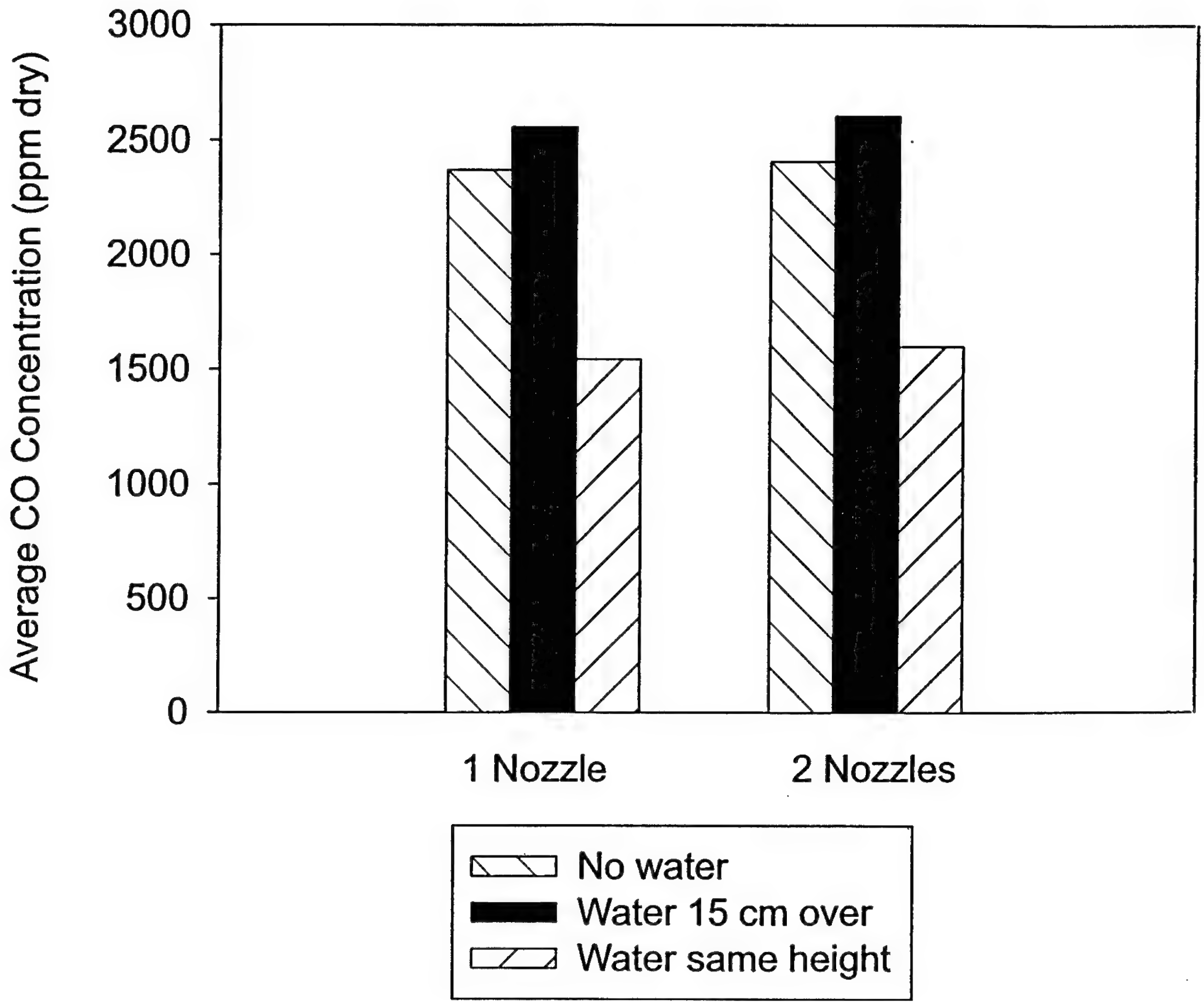

Fig. 15 – Comparison of carbon monoxide concentrations measured for aircraft mockup tests with and without water spray (water-to-fuel ratio = 9.1)

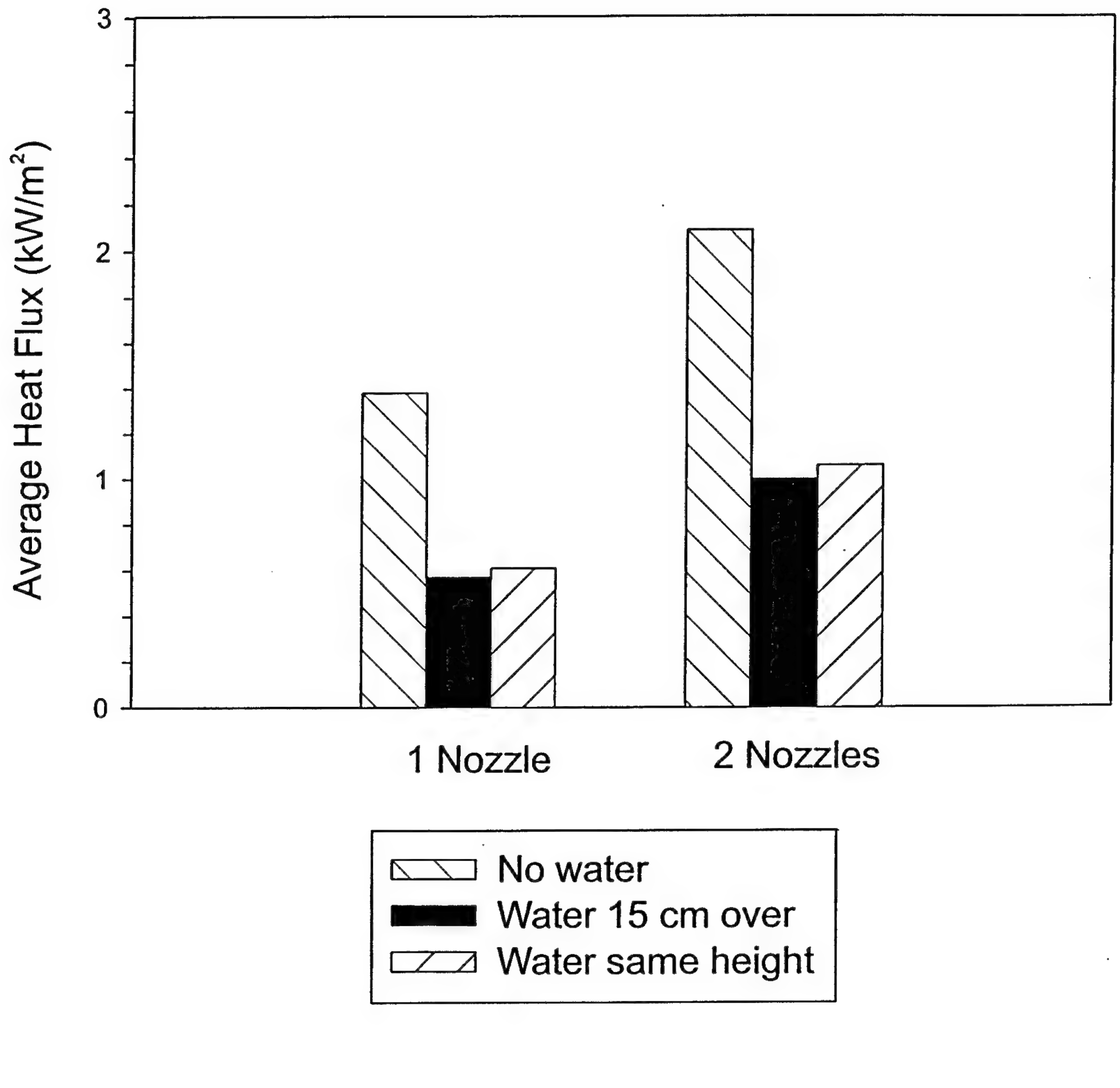

Fig. 16 – Comparison of heat fluxes measured for aircraft mockup tests with and without water spray (water-to-fuel ratio = 9.1)

6.2.2 Engine mockup tests

The engine mockup was simulated using two 55 gallon drums (Figure 17) mounted horizontally. Three configurations were examined each of which used an L48 nozzle for the fuel nozzle. This nozzle was positioned in the radial center of the drum, 20 cm from the back of the drum as shown in Figure 18. With configurations 1 and 2, the water nozzle was located at the top of the drum and directed down (see Figure 18). For configuration 1, the water nozzle was located 37 cm from the back of the drum, or 17 cm in front of the fuel nozzle. For configuration 2, the water nozzle was located 77 cm from the back of the drum, or 57 cm in front of the fuel nozzle. Figure 19 shows the arrangement for configuration 3. The water nozzle was at the same height as the fuel nozzle and 10 cm behind it. For this case, the fuel and water nozzle flow patterns were in the same direction (versus perpendicular to each other).

A summary of the average smoke yields and their corresponding standard deviations is provided in Table 4. Each of the three configurations produced good smoke abatement. The average percent reduction over the baseline scenario (i.e., no water spray) was greater than 80% for each configuration. The largest abatement was achieved in Configuration 2 where the water nozzle was directed perpendicular to the fuel nozzle and they were relatively close together. This reduction was 86%. In addition, this configuration appeared to produce the most realistic fire.

Table 4. Summary of Smoke Yields Measured for Engine Mockup

Description	Average Smoke Yield (g/g)	Standard Deviation	Percent Reduction (%)
Baseline	0.0189	0.0012	n/a
Water spray - Configuration 1	0.0026	0.00046	86
Water spray - Configuration 2	0.0035	0.0005	81
Water spray - Configuration 3	0.00277	0.001	85

6.3 Full Characterization Tests

The purpose of these tests was to perform an emissions characterization for the final design fires of the aircraft and fire mat mockups. Two additional species were measured in these tests: SO_2 and NO_x. Because of previous difficulties with heating the sample line and the THC analyzer, a different type of hydrocarbon analyzer was used during these tests (see Section 4.0). The aircraft tests were conducted with the water nozzle 1) 15 cm above the fuel nozzle and 2) at the same height (both oriented downward). Three water-to-fuel ratios (2, 2.5, and 9.1) and the effect of one versus two nozzles were examined.

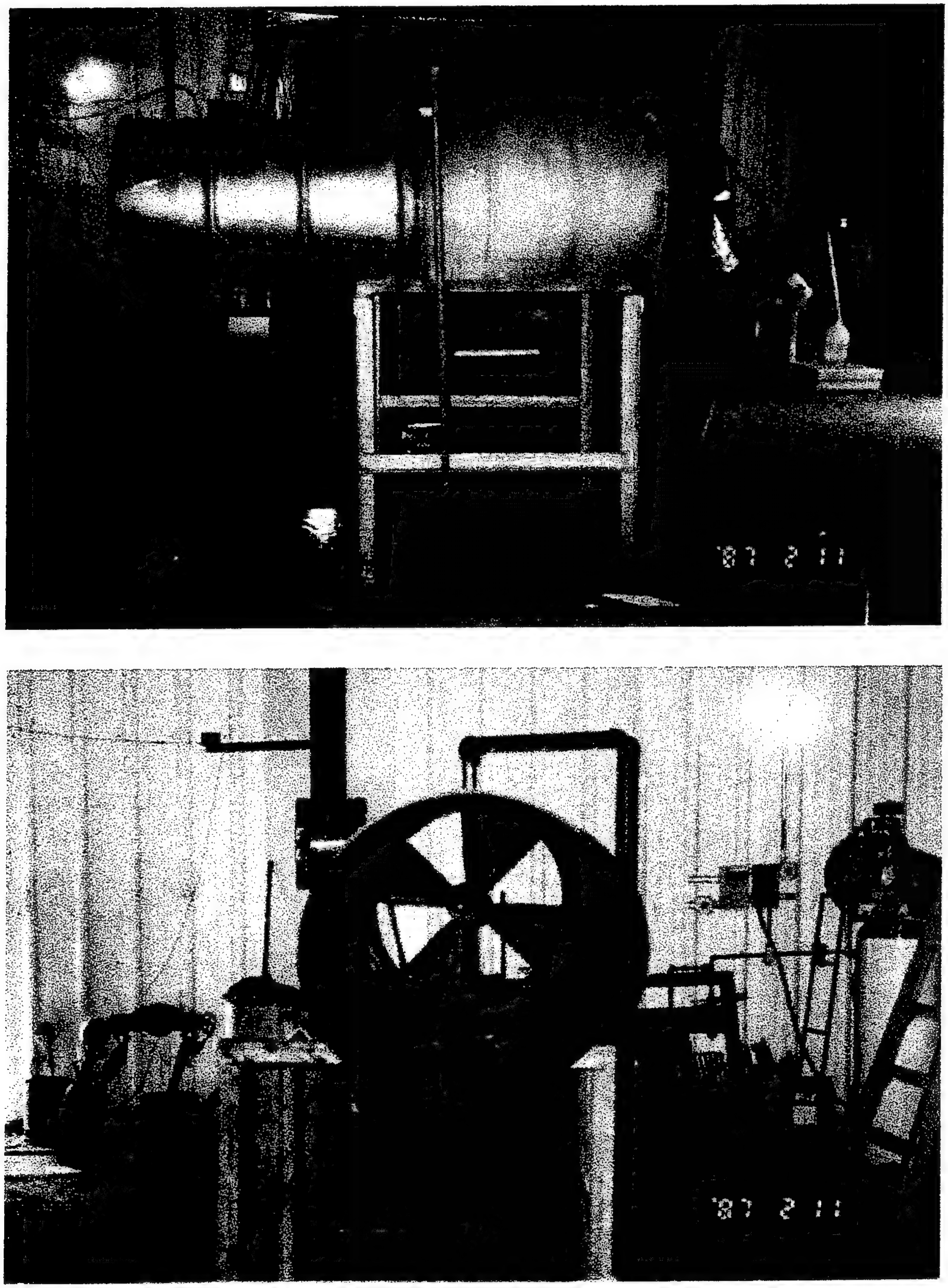

Fig. 17 — Engine mockup used in small-scale tests

Engine Mockup

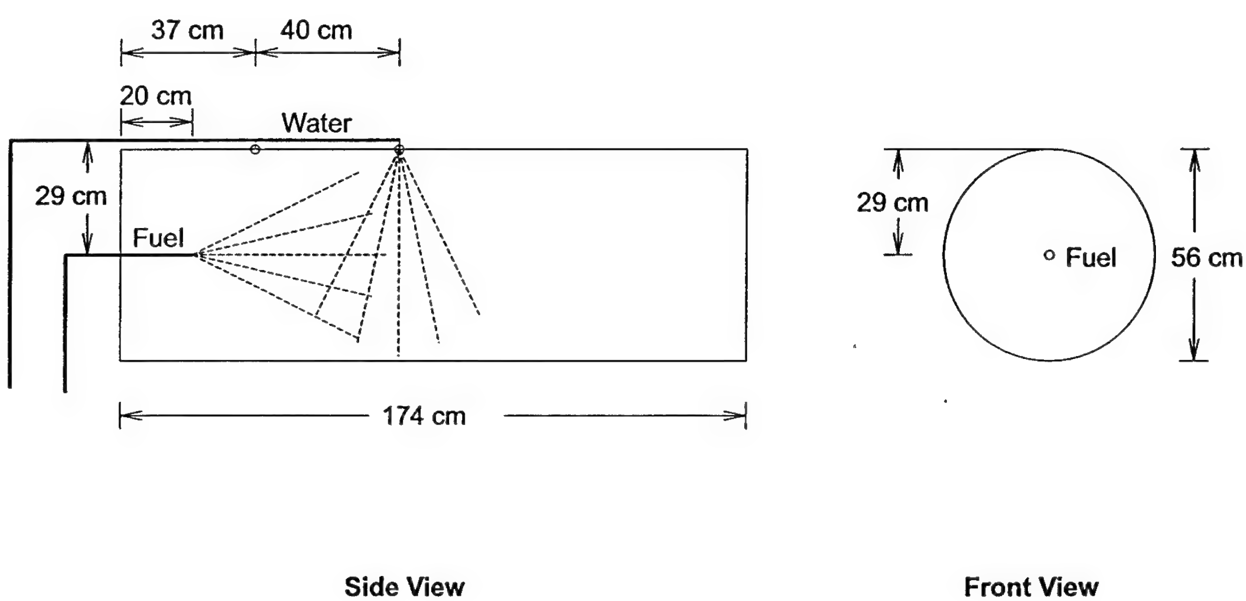

Fig. 18 – Schematic of fuel and water spray locations for configurations 1 and 2 for engine mockup tests

Engine Mockup

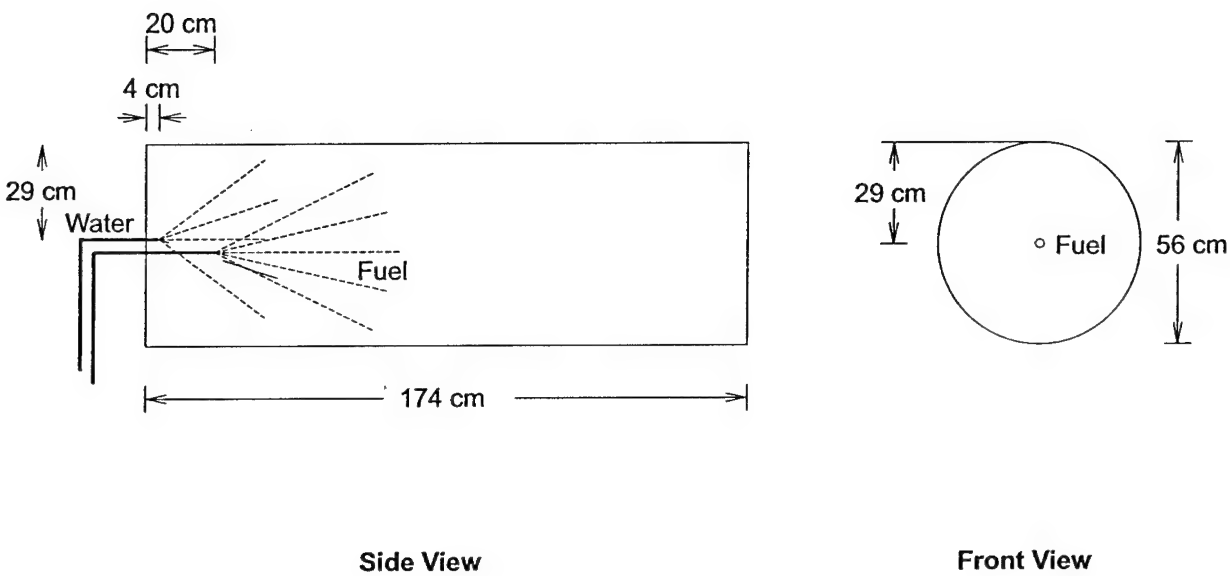

Fig. 19 – Schematic of fuel and water spray locations for configurations 3 for engine mockup tests

The fire mat tests used both types of fuel nozzles that were implemented in the fire mat design. These nozzles included the FF073 and the TF6XW manufactured by Bete Fog Nozzle. The FF073 nozzle produces a flat fan spray with an angle of 145°. The TF6XW nozzle is also a flat fan spray nozzle but with an angle of 360°. These nozzles were chosen because they most effectively simulated a pool fire. The water nozzles used were similar to those described for the other mockups (i.e., TF series) except that the spray angle was 170°. Due to limitations of the NRL-CBD burn building and associated hood system, it was necessary to reduce the fuel flow rate from the design rate for these fires. Further details about these nozzles and the fire mat design can be found in reference 8.

A summary of the aircraft mockup tests is shown in Table 5. This table includes the average value obtained for each particular scenario and the corresponding standard deviation. In some cases, the standard deviation is listed as 0 indicating that only one valid test was conducted. Baseline tests or tests without water overspray are denoted with bold letters. Total hydrocarbon measurements have been converted to represent parts per million C_1. The SO_2 measurements have been corrected for the analyzer offset measured at the beginning of the test. In some tests, this changed the concentrations by as much as 12 ppm in either direction.

Difficulties were experienced with the complete removal of water from the gas sample line. Therefore, it is uncertain if all of the generated SO_2 was measured. An analysis of the fuel by Penniman and Browne, Inc., reported that the sulfur content was 0.6 % by weight. Assuming stoichiometric combustion and that all sulfur reacted to SO_2, the maximum concentration would be 40 ppm. In some tests concentrations as high as 60 ppm were measured while in others, concentrations as low as 10 ppm were measured. Despite these difficulties, SO_2 concentrations showed a decreasing trend when water spray was added.

Smoke yields, carbon monoxide concentrations, and heat fluxes followed the same trends discussed above in Section 6.2.1. The smoke yield decreased when water spray was added. This effect was enhanced when the water spray nozzle was located at the same height as the fuel spray nozzle. The tests with two L48 fuel nozzles also show that the smoke reduction was greater when the water-to-fuel ratio was increased. Carbon monoxide concentrations show that the amount of CO was significantly reduced only when the water spray nozzle was at the same height as the fuel nozzle. It is also shown from results of one and two L48 fuel nozzle tests, with a fuel flow rate of 1.7 Lpm, that the CO concentration increased when the water spray nozzle was located 15 cm above the fuel nozzle. This trend does not hold for the tests with two L48 fuel nozzles at a flow rate of 2.0 Lpm.

Based on total heat flux measurements, the fire became less intense when water was added. Total hydrocarbon, NO_x, and SO_2 concentrations decreased when water spray was added. The reduction in THC and NO_x concentrations was greater when the water and fuel nozzle(s) were located at the same height. Furthermore, the reduction in SO_2 concentrations increased when the water-to-fuel ratio increased.

Results of the fire mat tests are shown in Table 6. As with the aircraft and engine mockup, the smoke yields decreased with water addition. However, this reduction was not as dramatic as that measured in the aircraft and engine mockup configurations. Carbon monoxide,

Table 5. Average Measurements for Tests Using Aircraft Configurations

Description	Fuel Flow Rate (Lpm per nozzle)	Water Flow Rate (Lpm per nozzle)	Water-to-Fuel Ratio	Smoke Yield Avg./Std Dev.	CO (ppm) Avg./Std. Dev.	THC (ppm C_1) Avg./Std. Dev.	NO_x (ppm) Avg./Std. Dev.	SO_2 (ppm) Avg./Std. Dev.	Heat Flux (kW/m^2) Avg./ Std. Dev.
L48	**1.7**	**0**	**n/a**	**0.018 / 0.0021**	**2371 / 35**	**17645 / 9671**	**12 / 7**	**34 / 19**	**1.38 / 0.11**
L48 w/ TF10FC 15 cm above	1.7	15.1	9.1	0.0027 / 0	2557 / 620	14752 / 646	2 / 0.3	16 / 9	0.57 / 0.03
L48 w/ TF10FC at same height	1.7	15.1	9.1	0.00153 / 0.0008	1543 / 84	8352 / 957	6 / 2	21 / 1	0.61 / 0.07
Two L48	**1.7**	**0**	**n/a**	**0.0163 / 0.0059**	**2408 / 184**	**16727 / 6924**	**13 / 2**	**40 / 18**	**2.09 / .018**
Two L48 w/ two TF10FC 15 cm above	1.7	15.1	9.1	0.0048 / 0.0004	2605 / 137	13931 / 1713	5 / 2	25 / 4	1.06 / 0.08
Two L48 w/ two TF10FC at same height	1.7	15.1	9.1	0.00067 / 0.00006	1598 / 52	7070 / 343	5 / 1	15 / 1	1.0 / 0.005
Two L48 @ 1.67 Lpm each w/ two TF6FC @ 4.09 Lpm each (same height)	1.7	4.1	2.5	0.0081 / 0	1699 / 0	12835 / 0	6 / 0	38 / 0	2.13 / 0
Two L48	**2.0**	**0**	**n/a**	**0.0192 / 0.005**	**2167 / 606**	**10370 / 3714**	**10 / 3**	**40 / 24**	**2.8 / 0.11**
Two L48 w/ two TF6FC 15 cm above	2.0	4.1	4	0.00945 / 0.0005	1877 / 16	10502 / 2144	6 / 0.4	34 / 6	2.1 / 0.09

Table 6. Average Measurements for Tests Using Fire Mat Configurations

Description	Fuel Flow Rate (Lpm per nozzle	Water Flow Rate (Lpm per nozzle)	Water-to-Fuel ratio	Smoke Yield Avg./Std Dev.	CO (ppm) Avg./Std. Dev.	THC (ppm C_1) Avg./Std. Dev.	NO_x (ppm) Avg./Std. Dev.	SO_2 (ppm) Avg./Std. Dev.	Heat Flux (kW/m^2) Avg./ Std. Dev.
FF073	**4.2**	**0**	**n/a**	**0.00565 / 0.00007**	**2525 / 97**	**12431 / 1110**	**2 / 0.1**	**45 / 3**	**1.8 / 0.02**
FF073 w/ TF12170	4.2	18.3	4.4	0.0048 / 0	1992 / 0	8303 / 0	0.2 / 0	60 / 0	1.8 / 0
TF6XW	**4.2**	**0**	**n/a**	**0.0072 / 0.006**	**1034 / 55**	**2142 / 454**	**8 / 4**	**28 / 10**	**2.0 / 0.03**
TF6XW w/ TF12170	4.2	14.4	3.5	0.0049 / 0	877 / 0	1527 / 0	4 / 0	17 / 0	2.1 / 0
TF6XW w/ TF12170	4.2	18.3	4.4	0.0048 / 0.0019	1232 / 175	2604 / 648	3 / 3	37 / 21	1.7 / 0.3
TF6XW w/ two F12170	4.2	18.3	8.7	0.0035 / 0.0007	2039 / 638	3263 / 0	4 / 0	30 / 19	1.2 / 0.06

THC, and SO_2 concentration measurements did not show a clear trend with respect to water addition. For tests using the TF6XW fuel nozzle, these emissions increased when water spray was added. However, a decrease in NO_x concentrations was measured with both fuel nozzles. Because of NRL-CBD burn building limitations, these tests were conducted with a fuel pressure of 138 kPa (20 psi). This pressure borders on the range of acceptable operating pressures and may have contributed to these inconsistencies. Heat flux measurements show that the effect of water spray on the fire intensity was not as significant as that measured during aircraft mockup tests.

It is important to note that it is difficult to form any scientific conclusions when considering the large standard deviations listed in Tables 5 and 6. These deviations show the difficulty in making these measurements. Considering the dilution rates measured (generally between 20 and 40), the measured concentrations were within the accuracy of the analyzers.

Currently, emissions (i.e., CO, THC, NO_x, and SO_2) from fire training facilities cannot be accurately predicted. The values listed in AP-42 were not intended for this type of application [6]. Furthermore, current test data and previous test data [5] show that emissions may be significantly underpredicted if AP-42 emissions factors are used. As a result, emissions factors for CO, THC, NO_x, and SO_2 were calculated using the final characterization data for single nozzle test results with water spray. The measurements used in the calculations were taken from tests which were closest to the design fires. These values are listed below in Table 7.

Table 7. Estimated Emissions Based on Full Characterization Tests

Fire Type/Scenario	Fuel Use gal/yr	THCs TPY	CO TPY	SO_2 TPY	NO_x TPY
Mass Conflagration	15,497	3.06	0.90	0.06	0.00
Debris	13,933	2.75	0.81	0.06	0.00
Aircraft	26,816	5.29	1.56	0.11	0.01
Engine	440	0.09	0.03	0.00	0.00
Cascade	784	0.15	0.05	0.00	0.00
Sub - Total:	57,470	11.34	3.33	0.23	0.01
Fire Mats:	284,700	56.14	16.50	1.14	0.05
TOTAL:	342,170	67.46	19.85	1.37	0.06
Emission Factor					
(lbs per 1000 gal fuel)		490-495	110-180	7-12	0.3-0.5

It should be noted that both aircraft and fire mat test results indicate that the emissions for a single nozzle cannot be scaled directly to predict emissions for tests with two nozzles. This was noted previously in Section 6.2.1 for CO emissions. In addition, results shown in Tables 5 and 6

show that this trend holds true for other non-visible emissions (THC, NO_x, and SO_2). The emissions factors calculated and shown in Table 7 use single nozzle data. While it is recognized that these values have a significant degree of scatter, they represent the first attempt at properly characterizing the emissions from fire trainers. Based on the species concentration trends observed for single and double nozzle tests, it is believed that emissions factors based on single nozzle data will overpredict the emissions and thus provide a conservative emissions estimate. Emissions from double nozzle tests are significantly less than two times the emissions from single nozzle tests.

7.0 SMOKE REDUCTION MECHANISMS

Initial smoke abatement designs utilized the concept of "water overspray" where the water nozzle sprayed down over the fuel nozzle. This suggested that the water was scrubbing the soot out of the fire effluent. However, the results from these series of tests show that this is not the primary mechanism. During these tests, there was little to no water remaining (hitting the pan) from the water spray. Instead, it was vaporized and carried up by the fire plume. Therefore, there is no evidence that the soot was being scrubbed. The smoke reduction was more dramatic when the water was sprayed into the fuel reaction zone. This observation is supported by the effectiveness of the same height, side-by-side fuel/water nozzle configuration.

There are two potential mechanisms which may play a key role in smoke reduction. The first of these mechanisms is a combination of a chemical and thermodynamic effect [12]. It has been hypothesized that the addition of water in near limit flames (i.e., near the edges of the flame where soot is formed) will result in a larger OH radical pool which in turn will promote oxidation of unburned hydrocarbons and reduce soot [13,14]. This effect has been demonstrated experimentally for limited rates of water addition in small-scale counterflow diffusion flames [14]. The second possibility is that the water spray generates more turbulence around the fire plume. This turbulence may result in better air entrainment into the fire plume. Increasing the air entrainment rate will allow the fire to burn closer to its stoichiometric limits. The closer the fire is to a stoichiometric fuel/air mixture, the cleaner it will burn. There was not sufficient information from these tests or in the literature to determine which mechanism or mechanisms are predominant for reducing smoke in these tests.

8.0 CONCLUSIONS

Small-scale tests were performed to improve smoke abatement technology for firefighter training facilities. Results showed that water spray can substantially reduce the amount of visible smoke generated by training fires. It was also demonstrated that smoke reduction will decrease as the water-to-fuel ratio is increased. Smoke yield reductions as high as 96% were measured with a water-to-fuel ratio of 9.1. The primary tradeoff which occurs as a result of water spray is the reduction in fire intensity. However, this reduction does not compromise the firefighting challenge and realism necessary for training fires.

Three fuel additives were examined: MTBE, ethanol, and ferrocene. MTBE and ethanol were not suitable additives since they were not effective at reducing smoke production and they lowered the fuel flashpoint to an unsafe level. However, the use of ferrocene was promising. Significant smoke reduction (approximately 83%) was achieved with a concentration as low as 0.15% by mass. One advantage of ferrocene versus water spray is that the fire intensity is only slightly reduced. Use of this additive would require an environmental and health analysis. The use of a water and fuel emulsion also provided good smoke reduction. This technique was not pursued further due to logistical concerns and potential safety issues.

In general, the addition of water spray decreased all emissions. While this was always true for visible emissions, it was not always true for non-visible emissions. Emissions factors were developed that would represent the emissions from JP-5 training fires better than those currently listed in the latest edition of AP-42 [6]. The use of the emission factors developed in this study will tend to overestimate emissions.

Based on small-scale results in conjunction with full-scale testing, final designs were developed for the fire training facility at NATTC Pensacola. These designs have been implemented on the aircraft, cascade, engine and fire mat mockups.

9.0 REFERENCES

1. Department of the Navy, "Final Environmental Impact Statement for the Realignment of Naval Air Station - Pensacola, Florida, Chief of Naval Education and Training," September 1994.

2. Department of the Navy, "Application to Operate/Construct Air Pollution Sources for Carrier Deck Simulator and Fire Mats," Naval Air Station, Pensacola, FL, September 29, 1994.

3. Department of Environmental Protection, letter to Frederick K. Walker, Vice President, Greiner, Inc., State of Florida, Department of Environmental Protection, October 6, 1994.

4. Leonard, J.T., Williams, F.W., Roby, R. J., Scheffey, J. L. and Hamer, A.J., "Environmentally Friendly Fire Fighter Training Facilities - Combustion Testing Final Report," NRL Ltr Rpt 6180/0515.1, August 20, 1996.

5. Leonard, J.T., Burns, R.E., Gottuk, D.T., and Hamer, A.J., "Preliminary Smoke Abatement System Tests," NRL Ltr Rpt Ser 6180/0423.1, August 9, 1995.

6. *Compilation of Air Pollutant Emission Factors*, AP-42, U.S. Environmental Protection Agency, 1985.

7. *Compilation of Air Pollutant Emission Factors*, AP-42, 5th Edition, U.S. Environmental Protection Agency, January 1995.

8. Peatross, M.J., Verdonik, D.P., Ouellette, R., Horton, D., and Burns, R.E., "An Investigation of Air Emission Reduction Methods for Aircraft Rescue and Firefighter Training Fires: Full-scale Tests," prepared for Naval Sea Logistics Center under project 7507, Hughes Associates, Inc., Baltimore, MD, July 1997.

9. Janssens, M., and Parker, W.J., "Oxygen Consumption Calorimetry," *Heat Release Rate in Fires*, V. Babrauskas and S.J. Grayson, ed., Elsevier Applied Science, NY, 1992.

10. Mitchell, J.B.A., "Smoke Reduction from Burning Crude Oil Using Ferrocene and its Derivatives," *Combustion and Flame*, **86**, 1991, pp. 179-184.

11. Zhang, J. and Megaridis, C.M., "Soot Suppression by Ferrocene in Laminar Ethylene/Air Nonpremixed Flames," *Combustion and Flame*, **105**, 1996, pp. 528-540.

12. Glassman, I., "Soot Formation in Combustion Processes," *Twenty-Second International Symposium on Combustion*, The Combustion Institute, 1988, pp. 295-311.

13. Miyauchi, T., Mori, Y., and Yamaguchi, T., "Effect of Steam Addition on NO Formation," *Eighteenth International Symposium on Combustion*, The Combustion Institute, 1981, pp. 43-51.

14. Suh, J., and Atreya, A., "The Effect of Water Vapor on Counterflow Diffusion Flames," Proceedings of the International Conference on Fire Research and Engineering, Orlando, Florida, September 10-15, 1995, pp. 103-108.

APPENDIX A

K36 Smoke Abatement - Test Setup
Analyzer and Apparatus Check Sheet

Date ____________________

Check List

- __________ Gas analyzers calibrated (CO, CO_2, O_2, and THC)
- __________ ODM cleaned and checked
- __________ Total heat flux transducer set (water on)
- __________ TC in stack checked
- __________ Pressure transducers checked/power on
- __________ Trigger/flag box setup
- __________ Fuel supply set
- __________ H_2O supply set
- __________ Air supply set
- __________ Emergency fuel shut-off setup and checked
- __________ Extinguishers/firefighting apparatus setup/at hand

Setup Ranges

- __________ Fan speed pulley setting
- __________ O_2 analyzer range
- __________ THC analyzer range

Options Checklist

- __________ NO_X calibrated
- __________ SO_X calibrated
- __________ PM-10s calibrated

K36 Smoke Abatement – Test Data Sheet (Rev 2, Apr 96)

Test No. __________ Date __________________

Test Scenario: ____
____
____

Fuel _________________ Additive ____________

Fuel nozzle __________ Number of Nozzles _________

Fuel pressure (psi) _________ Fuel flow rate (gpm) _________

Air pressure (psi) _________ Air flow rate (cfm) _________

Height above pan _________ Orientation(s) _________

H_2O nozzle __________

Pressure (psi) _________ Flow rate (cfm) _________

Height above fuel _________ Height from Pan _________

Description____
____

Pre-test Check List

_________ Analyzer background reading checked (CO, CO_2, O_2, THC, ODM, NO_X and SO_X)

_________ Marker-board changed and video taken

_________ Data acquisition set with new file name

_________ Fuel set _________ H_2O supply set _________ Air Set

Pre-test Data List

_________ THC range

_________ Temperature

_________ Relative Humidity

_________ Barometric Pressure

_________ Fan Speed

K36 Smoke Abatement – Test Data Sheet (Continued)

Test No. __________ Date ____________________

Time (s)	Event
0	Data acquisition on (trigger on) and video cameras on
50	Heptane added to Pan
	Ignition (flag on)
	Fire extinguished (flag off)
	Stop data collection

Observations: ____

Visual - Smoke Opacity:__________________ Time______________________________

Visual - Smoke Opacity:__________________ Time______________________________

Picture No.__________ Description____

Picture No.__________ Description____

Picture No.__________ Description____

Picture No.__________ Description____

Picture No.__________ Description____

Picture No.__________ Description____